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Possible Measurements of Single and Double Spin Asymmetries with $HERA-\vec{N}$ ¹

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Abstract

The physics scope of a possible future experiment utilizing an internal polarized nucleon target in the HERA proton beam is discussed. By measuring single spin asymmetries in inclusive particle production at 820 GeV beam energy the higher-twist sector of perturbative QCD can be probed with good statistical sensitivity. To support the physics case for proton polarization at HERA, we consider the measurement of double spin asymmetries in photon plus jet production. It appears possible to determine the polarized gluon distribution in the range $0.1 \leq x_{gluon} \leq 0.4$ with good accuracy.

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1 Introduction

An experiment ('*HERA*– \vec{N} ') utilising an internal polarized nucleon target in the 820 GeV *HERA* proton beam would constitute a logical extension of the study at DESY, commenced with the *HERMES* experiment, of the nucleon structure by investigating in detail its spin degrees of freedom. Judged from today, this would be the only other place to study high energy nucleon–nucleon spin physics besides the envisaged dedicated RHIC spin program at BNL which is supposed to get started in about five years from now.

The internal polarized nucleon target offers unique features such as polarization above 80%, no or small dilution, and a high density up to 10^{14} atoms/cm² [1]. Moreover, only small systematic errors are expected when proton and neutron results extracted from hydrogen and deuterium gas data, respectively, are compared.

As long as the polarized target is operated in the unpolarized proton beam, *HERA*– \vec{N} would be focused on measurements of single spin asymmetries in different inclusive final states ('Phase I' physics) [2, 3, 4]. Once polarized protons should become available at *HERA*, the same set-up would be readily available to measure various kinds of double spin asymmetries. These 'Phase II' measurements would constitute an alternative – fixed target – approach to similar physics as it will be accessible to the collider experiments *STAR* and *PHENIX* at the low end of the RHIC energy scale ($\sqrt{s} \simeq 50$ GeV) [5].

In the following the physics capabilities of *HERA*– \vec{N} will be illustrated by selecting two specific measurements. As an example for Phase I physics, inclusive pion production will be shown to serve as a sensitive test of the QCD spin sector in the transition region between the non–perturbative and the perturbative regime. Photon plus jet production, chosen as an example for Phase II physics, will be shown to be suitable for measuring the polarized gluon distribution with a statistical accuracy comparable to that in future measurements at RHIC.

A more extended description of the present understanding of the prospects of polarized nucleon–nucleon physics at *HERA* is given in a separate paper [6] which describes the results of a recent workshop at DESY–Zeuthen.

2 Expected Size of Asymmetries

In the *unpolarized* *HERA* proton beam the physically interesting single spin asymmetry A_N arises from inverting the direction of the transversely oriented target polarization vector:

$$A_N = \frac{d\sigma(pN^\uparrow) - d\sigma(pN^\downarrow)}{d\sigma(pN^\uparrow) + d\sigma(pN^\downarrow)} \quad (1)$$

A_N is supposed to be very small in pQCD [7], as will be discussed below in more detail.

In a *polarized* proton beam the double spin asymmetry of primary interest is the normalized cross section difference between parallel and anti–parallel alignment of the longitudinally oriented beam and target polarization vectors:

$$A_{LL} = \frac{d\sigma(\vec{p}\vec{N}) - d\sigma(\vec{p}\overset{\leftarrow}{\vec{N}})}{d\sigma(\vec{p}\vec{N}) + d\sigma(\vec{p}\overset{\leftarrow}{\vec{N}})} \quad (2)$$

To assess the order of magnitude of an asymmetry measurable in the hadronic reaction $A + B \rightarrow C + (D) + X$ it has to be taken into account that on the parton level, usually several subprocesses $a + b \rightarrow c + d$ contribute. Utilizing the QCD factorization property the measured asymmetry can be represented as

$$A^{had} \sim (P_B) \cdot P_T \cdot \sum_{a,b} (A^a) \cdot A^b \cdot A^{ab} \cdot [A^c] \cdot [A^d] \quad (3)$$

where P_B and P_T are the average beam and target polarisation, respectively. Throughout the paper $P_B = 0.6$ and $P_T = 0.8$ are assumed. The average parton polarization in a fully polarized nucleon is believed to be $A^a, A^b \simeq 0.25 \dots 0.5$. The hard scattering asymmetry A^{ab} , completely calculable in pQCD for double spin asymmetries, ranges between 0.01 and 1. No reliable numbers are known yet for the fragmentation asymmetries A^c, A^d ; fortunately this dilution does not appear when photon, Drell-Yan and/or jet production is considered.

Taking into account that P_B and A^a do not appear for unpolarized beams when inserting the above numbers into eq.(3) we find that the measurable asymmetry values might range from 0.001 to about 0.25. Hence precision measurements with statistical sensitivities of 0.01 or better are required to study the spin dependence of nucleon-nucleon collisions. At the same time a careful assessment of systematic errors is indispensable.

3 Luminosity and Sensitivity

The statistical sensitivity in measuring a spin asymmetry A is given by [8]

$$\delta A = \frac{1}{P_B \cdot P_T} \cdot \frac{1}{\sqrt{C \cdot \mathcal{L} \cdot T}} \cdot \frac{1}{\sqrt{\sigma}} , \quad (4)$$

$C \simeq 50\%$ represents the anticipated combined trigger and reconstruction efficiency. Using $\bar{I}_B = 80 \text{ mA} = 0.5 \cdot 10^{18} \text{ s}^{-1}$ as a realistic figure for the 1996 average HERA proton beam current and a realistic polarized target density of $n_T = 3 \cdot 10^{13} \text{ atoms/cm}^2$ [1] the projected luminosity becomes

$$\mathcal{L} = n_T \cdot \bar{I}_B = 1.5 \cdot 10^{31} \text{ cm}^{-2} \text{s}^{-1} . \quad (5)$$

Assuming for the total running time an equivalent of $T = 1.6 \cdot 10^7 \text{ s}$ at 100 % efficiency the integrated luminosity is obtained as

$$\mathcal{L} \cdot T = 240 \text{ pb}^{-1} \quad (6)$$

The resulting sensitivities are given by

$$\begin{aligned} \delta A_{ssa} &= 0.10 / \sqrt{\sigma / [\text{pb}]} & \text{for single spin asymmetries and} \\ \delta A_{dsa} &= 0.17 / \sqrt{\sigma / [\text{pb}]} & \text{for double spin asymmetries.} \end{aligned}$$

These sensitivities do not include the spectrometer acceptance. In a typical fixed target experiment the main reduction is imposed by the limited azimuthal coverage which decreases the acceptance by about $1/\sqrt{1/3} \simeq 2$. On the other hand, experience from UA6 at CERN indicates that after having gained some practical running experience it might turn out feasible to operate the polarized gas target at a 2 or 3 times higher density without seriously affecting the proton beam lifetime. In addition, proton currents much higher than the original HERA design value of 160 mA will presumably be provided later in a possible HERA high luminosity scenario. Thus eventually a net improvement in sensitivity by a factor of 2 or better can be realistically expected.

Using 1995 realistic HERA conditions (including 33% combined up-time for accelerator and experiment) the integrated luminosity calculated in eq.(6) would correspond to about 3 calendar years of machine operation with 6 months physics running per year. Taking account of the improvements expected to have been made by the time of a possible *HERA- \vec{N}* experiment as noted above, leads to a running time of about 1 to 2 real years required to collect 240 pb^{-1} .

4 Kinematics

In fig. 1 the interdependence between laboratory angle and laboratory momentum for inclusive pion production is shown as a function of x_F and p_T .

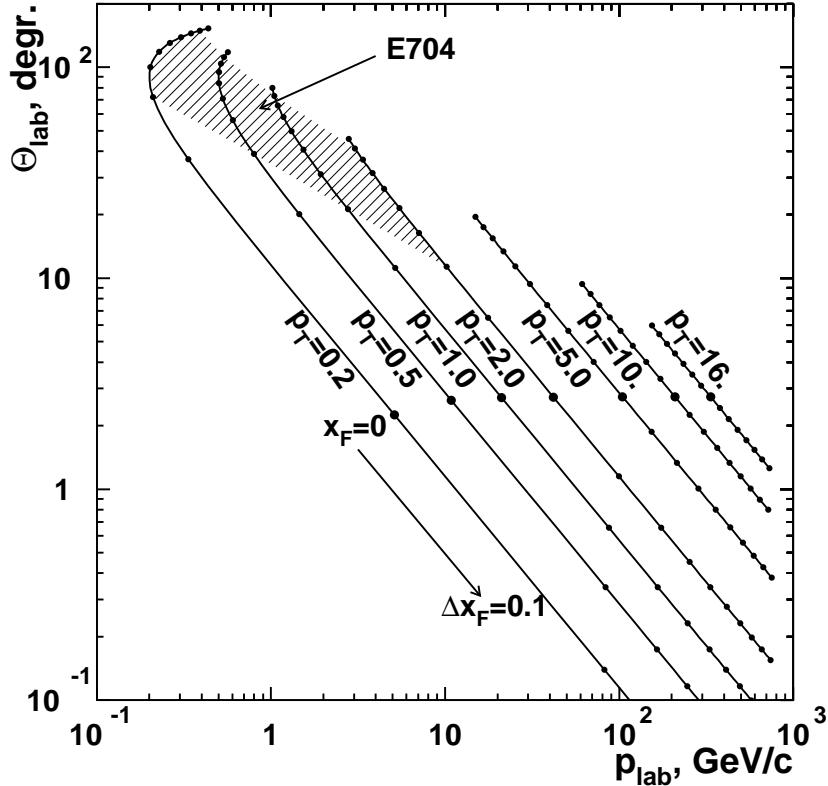


Figure 1: *Kinematics for inclusive pion production.*

The hatched area corresponds to the fragmentation region of the polarized nucleon, for which the *E704* Collaboration has found significant non-zero values in the pion single spin asymmetry [9]. For easier comparison this area is drawn in the backward hemisphere here since during Phase I of *HERA- \vec{N}* the *target* nucleon would carry the polarization, whereas in *E704* the polarized *beam* was hitting an unpolarized target. It is obvious that in order to check the *E704* results and to measure the hitherto unknown p_T dependence of single spin asymmetries at large enough $|x_F|$ the spectrometer must be able to detect pions emitted under rather large laboratory angles ($\Theta_{lab} \geq 10$ degrees) which implies low momenta ($p_{lab} \leq 10$ GeV/c). We note that the measurement of singly polarized *elastic* scattering, where significant non-zero results [10, 11] are also at variance with the pQCD prediction $A_N \simeq 0$, requires recoil proton detection under large laboratory angles as well.

In contrast, the study of double spin asymmetries during Phase II of *HERA- \vec{N}* (e.g. in photon plus jet production) would require to detect *both* photon and jet; rather small laboratory angles (a few tens of milliradians) are involved. Altogether it can be concluded that the *HERA- \vec{N}* apparatus should have a wide-aperture spectrometer to ensure that a sufficiently broad spin physics program can be realized.

5 Single Spin Asymmetries

Single spin asymmetries in large p_T inclusive production, both in proton-nucleon and lepton-nucleon interactions have recently received much attention [12]. The naive expectation from perturbative QCD that they should be zero has been proven to be false, both experimentally and theoretically. It is now clear that twist-3 effects are responsible for these asymmetries, which come out to be zero only in leading twist-2 perturbative QCD.

Several models and theoretical analyses suggest higher-twist effects: there might be twist-3 dynamical contributions (hard scattering higher-twists [13]); there might also be intrinsic k_\perp effects, both in the quark fragmentation process [14, 15] and in the quark distribution functions [7, 16, 17, 18]. The latter are not by themselves higher-twist contributions but rather non-perturbative universal nucleon properties giving rise to twist-3 contributions when convoluted with the hard scattering cross sections. The dynamical contributions result from a short distance part calculable in perturbative QCD combined with a long distance part related to quark-gluon correlations [13].

We consider the hadron level reaction $p + N^\uparrow \rightarrow h + X$ and a corresponding singly polarized partonic subprocess $a + b^\uparrow \rightarrow c + d$. According to the leading twist QCD factorization theorem the single spin asymmetry A_N defined in eq. (1) can be represented as

$$A_N \sim \sum_{ab \rightarrow cd} f_{a/p} \otimes \Delta_T f_{b/N} \otimes \hat{a}_N \otimes D_{h/c} \quad (7)$$

with $\Delta_T f_{b/N} = f_{b^\uparrow/N^\uparrow} - f_{b^\downarrow/N^\uparrow}$. The number densities of 'beam partons' a and polarized 'target partons' b^\uparrow in their parent nucleon are denoted by $f_{a/p}$ and $f_{b^\uparrow/N^\uparrow}$, respectively. $D_{h/c}$ is the number density of the hadron h from fragmentation of the outgoing parton c . Finally, \hat{a}_N is the single spin asymmetry for the parton subprocess under consideration, which is zero, thus giving $A_N = 0$.

However, as we said above, intrinsic k_\perp and higher-twist effects might modify the above equation leading to twist-3 non-zero contributions to A_N ranging between 10 and 20%.

It is tempting to try a separation of these possible contributions to single spin asymmetries by considering together the results of different reactions and final states, respectively:

- $pN^\uparrow \rightarrow hX$

In this process, measurable with *HERA*– \vec{N} , all kinds of higher-twist contributions may be present; those related to k_\perp effects in the fragmentation function have been considered in Ref. [15] and those related to k_\perp effects in the distribution function in Refs. [17, 18]. This asymmetry alone could not help in evaluating the relative importance of the different terms.

- $pN^\uparrow \rightarrow \gamma X$ or $pN^\uparrow \rightarrow \mu^+ \mu^- X$

These reactions, measurable with *HERA*– \vec{N} as well, contain no fragmentation process. Possible sources of non-zero single spin asymmetries are in the hard scattering process or the quark distribution functions.

- $lN^\uparrow \rightarrow hX$

In such a process, measurable with *HERMES* [19] or *COMPASS* [20], the single spin asymmetry can originate either from hard scattering or from k_\perp effects in the fragmentation function, but not in the distribution functions, as soft initial state interactions are suppressed by powers of α_{em} .

- $lp^\uparrow \rightarrow \mu^+ \mu^- X, \quad lp^\uparrow \rightarrow \gamma X, \quad \gamma p^\uparrow \rightarrow \gamma X$

Each of these processes yields a single spin asymmetry which cannot originate from distribution or fragmentation k_\perp effects; it may only be due to higher-twist hard scattering effects, which would thus be isolated. The first two processes can – at least in principle – be measured with *HERMES*

or *COMPASS*, the last one possibly using quasi-real photons with *H1* or *ZEUS*. It is not obvious, however, that the counting rate for these processes will be sufficient to utilize its apparent 'theoretical usefulness' for disentangling the different fundamental components involved in single spin asymmetries. It is clear from the above discussion that a careful and complete study of single spin asymmetries in several processes might be a unique way of understanding the origin and importance of twist-3 contributions in inclusive hadronic interactions. In addition it might also allow a determination of fundamental non-perturbative properties of quarks inside polarized nucleons and of polarized quark fragmentation. Such properties should be of universal value and applicability and their knowledge might be as important as the knowledge of unpolarized distribution and fragmentation functions.

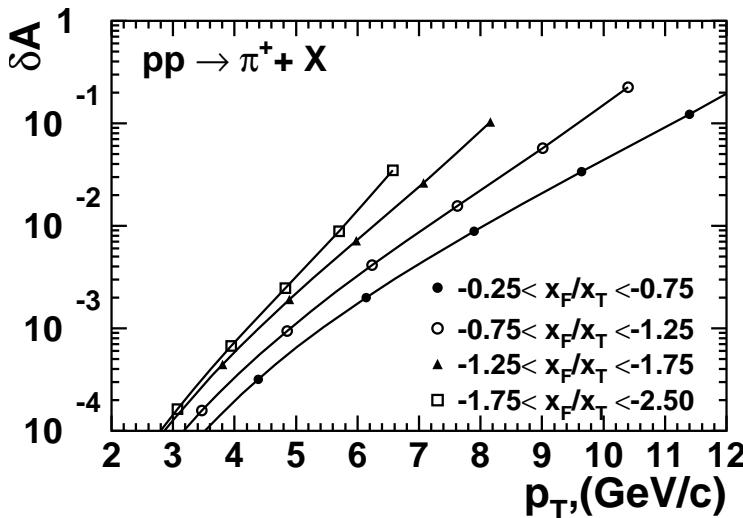


Figure 2: *Projected statistical accuracy vs. p_T in different sectors of $\tilde{x}_F = x_F/x_T$.*

We calculated the statistical sensitivity for inclusive pion production under the above described *HERA- \vec{N}* conditions [6]. Studying the (Monte Carlo) data in a 2-dimensional (p_T, x_F) binning with a cell size of $\Delta p_T \times \Delta p_L = 2 \times 2$ GeV 2 it turns out that the p_T values accessible to *HERA- \vec{N}* are significantly larger than in the *E704* experiment. The combined p_T dependence of all higher-twist effects involved can be measured with good accuracy ($\delta A_N \leq 0.05$) up to transverse momenta of about 10 GeV/c in the central region $|x_F| < 0.2$ and up to 6 GeV/c in the target fragmentation region. To make sure that the genuine p_T dependence of the single spin asymmetry is not spoiled by other implicit dependencies we write it in its most general form as predicted by kinematics and dimensional analysis

$$A_N = \frac{M}{p_T} \cdot f(x_F, x_T) \quad (8)$$

with $x_T = p_T/p_T^{max} = 2p_T/\sqrt{s}$. In a good approximation the energy dependence of x_T can be neglected allowing for the simplification

$$A_N = \frac{M}{p_T} \cdot f(\tilde{x}_F) \quad (9)$$

where $\tilde{x}_F = x_F/x_T$. This behaviour can be clearly checked if the data is binned in an appropriate way, i.e. within angular sectors having about the same \tilde{x}_F value. When considering a certain region

of high, i.e. target fragmentation like x_F values (say, -0.4 to -0.8), each angular sector covers a rather small range in p_T , only. Each of these sectors being characterized by its average \tilde{x}_F then delivers its own p_T dependence which is scaled among each other by the difference in the function $f(\tilde{x}_F)$. Considering all \tilde{x}_F bins together, a clear picture is supposed to emerge on the overall p_T dependence of higher-twist effects. The sensitivity within each sector vs. p_T is displayed in fig. 2. As can be seen, there is good sensitivity ($\delta A_N \leq 0.05$) up to $p_T \simeq 10$ GeV, hence the kinematical range accessible to $HERA-\vec{N}$ is well suited to 'scan' over the onset region of perturbative QCD.

6 Double Spin Asymmetries

Perturbative QCD allows for a simple calculation of Born double spin asymmetries for various 2→2 subprocesses at the partonic level. The one-loop radiative corrections to various subprocesses have now been calculated [21], they produce only small changes in the asymmetry in comparison with the leading order. Relying on factorization a rich spectrum of hadronic level asymmetries is predicted which constitutes the backbone of the RHIC spin physics program [22].

The measurement of A_{LL} in certain final states (e.g. photon plus jet) is presently considered to be one of the most promising methods to determine the (normalized) polarized gluon distribution $\Delta G/G$. Hence in the following an estimate is given for the $HERA-\vec{N}$ sensitivity to perform such a measurement in the doubly polarized mode ('Phase II'). When both photon and jet are detected in the hadronic final state the Gluon–Compton subprocess $q + g \rightarrow \gamma + q$ dominates over the quark–antiquark annihilation $q + \bar{q} \rightarrow \gamma + g$ if the transverse momentum exceeds a few GeV/c. Describing the former one by partonic formula [6] yields for the polarized and unpolarized cross sections

$$\Delta\sigma = \sum_f e_f^2 \cdot \Delta q \cdot \Delta G \cdot \Delta\hat{\sigma} \sim g_1 \cdot \Delta G \cdot \Delta\hat{\sigma}, \quad (10)$$

$$\sigma = \sum_f e_f^2 \cdot q \cdot G \cdot \hat{\sigma} \sim F_1 \cdot G \cdot \hat{\sigma}, \quad (11)$$

respectively. Hence the double spin asymmetry eq.(2) can be written as

$$A_{LL} = A_{DIS} \cdot \hat{a}_{LL} \cdot \frac{\Delta G}{G} \quad (12)$$

Here $A_{DIS} = g_1/F_1$ is the asymmetry measured in doubly polarized lepton nucleon scattering and the partonic level asymmetry \hat{a}_{LL} is completely calculable in pQCD. The absolute statistical error of $\Delta G/G$ is readily obtained as

$$\delta\left[\frac{\Delta G}{G}\right] = \frac{\delta A_{LL}}{A_{DIS} \cdot \hat{a}_{LL}}. \quad (13)$$

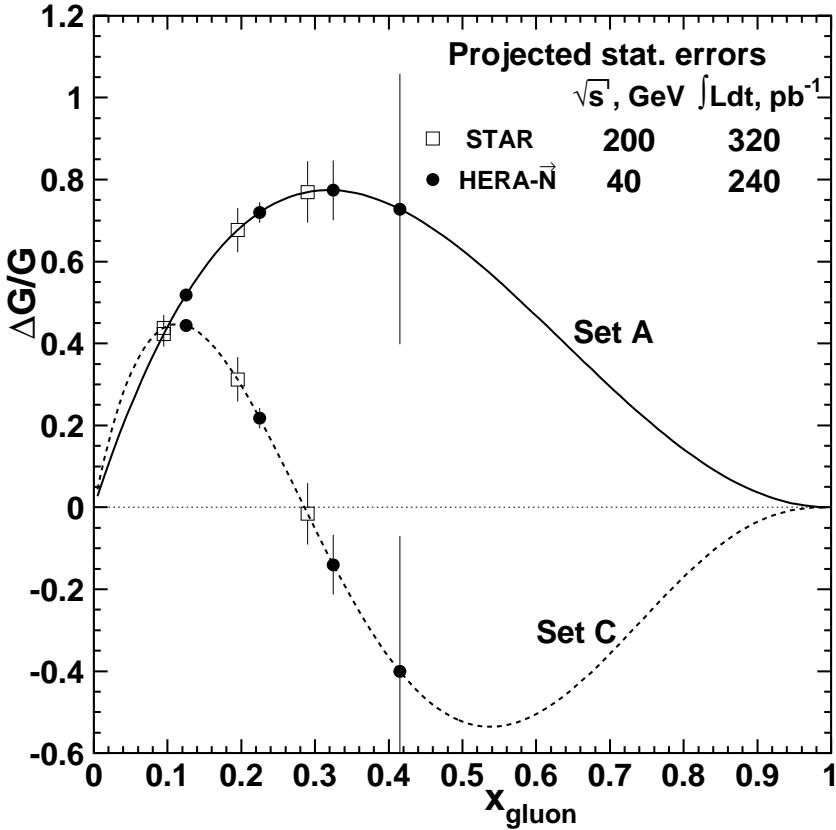


Figure 3: *Typical predictions for the polarized gluon distribution confronted with the projected statistical errors expected for the HERA- \vec{N} and STAR experiments.*

In fig. 3 we reproduce two typical predictions for the polarized gluon distribution (Gehrmann and Stirling [23], set A and C) in conjunction with the projected $HERA-\vec{N}$ statistical errors. The errors show clearly that in the region $0.1 \leq x_g \leq 0.4$ a significant result can be expected. This statement will very probably remain valid if once the systematic errors will have been estimated. Note that in this first approximation the jet and photon reconstruction efficiencies were not included. From preliminary jet studies [6] it can be anticipated that a serious deterioration will occur only for lower p_T -values, i.e. for the left-most point in fig. 3. For comparison, we show the corresponding projected statistical errors for *STAR* running at 200 GeV c.m. energy [24]. As can be seen, the measurement of $\Delta G/G$ in doubly polarized nucleon-nucleon collisions at *HERA* will yield results competitive with those predicted for *RHIC*. As a word of caution we note that the projected *STAR* errors available today are based upon much more detailed studies than those shown here for $HERA-\vec{N}$.

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